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Early-season, Low-dose Applications of Endothall to Selectively Control Curlyleaf Pondweed in Minnesota Lakes

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PURPOSE: This multi-year study was designed to evaluate early spring applications of low doses of endothall to selectively control the invasive submersed plant curlyleaf pondweed (*Potamogeton crispus* L.) in Minnesota lakes.

BACKGROUND: Curlyleaf pondweed is an invasive submersed plant that infests water bodies in the northern United States. It typically overwinters as a quiescent, but photosynthetically active plant, even under ice cover (Nichols and Shaw 1986). Following spring ice-out, these plants begin accelerated growth under low light, before most native plants break dormancy, forming dense surface canopies in May or June (Wehrmeister and Stuckey 1992). These canopies limit growth of native plants, negatively impact water quality, and interfere with navigation and recreation (Bolduan et al. 1994). Selective removal of exotic plants, like curlyleaf pondweed, can improve recreational use of lakes, stabilize water quality, and increase native plant diversity (Getsinger et al. 1997).

The potential for restoring native aquatic plant communities using herbicides in a selective manner has been documented in small-scale studies (Netherland et al. 1997; Poovey et al. 2002; Skogerboe and Getsinger 2001, 2002; Sprecher et al. 1998) and in field demonstrations (Getsinger et al. 2002, Madsen et al. 2002, Poovey et al. 2004). Because herbicide sensitivity can vary between plant species, selective control of target weeds depends on the herbicide used and the composition of native plant communities in the treated area.

Endothall (7-oxabicyclo[2.2.1]heptane-2-3dicarboxylic acid), a broad spectrum herbicide, is effective in controlling a wide range of submersed aquatic plants (Westerdahl and Getsinger 1988). The mode of action for endothall has been described as a contact-type herbicide that may cause rapid membrane disruption in plant cells, while inhibiting oxygen consumption ((Ashton and Crafts 1981, MacDonald et al. 1993). However, other evidence indicates that endothall may be slowly taken up by submersed plants (Haller and Sutton 1973, Reinert and Rogers 1986, Van and Conant 1988).

Both dicotyledons, such as Eurasian watermilfoil (*Myriophyllum spicatum* L.), and moncotyledons, such as hydrilla (*Hydrilla verticillata* L.f. Royle*)* and curlyleaf pondweed (Netherland et al. 1991, 2000; Madsen 1997a; Pennington et al. 2001; Poovey et al. 2002; Skogerboe et al. 2004; Westerdahl and Getsinger 1988) are controlled by endothall. However, native plant sensitivity to the herbicide varies greatly among species (Skogerboe and Getsinger 2001, 2002). Pondweeds – such as Illinois pondweed (*Potamogeton illinoensis* Morong.) and sago pondweed (*Stukenia pectinata* L.) – and southern naiad [*Najas guadalupensis* (Sprengel) Magnus] are very sensitive to endothall, while coontail (*Ceratophyllum demersum* L.) is moderately sensitive. Others species such as elodea (*Elodea canadensis* Michx), wildcelery (*Vallisneria americana* L.), water stargrass [*Zosterella dubia* (Jacq.) MacM.], and many floating-leaf and emergent species are more tolerant of endothall.

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Therefore, endothall has the potential to selectively control curlyleaf pondweed in sites where native plants, other than pondweeds, dominate the plant community.

Applying herbicides in early spring can potentially increase selectivity by targeting curlyleaf pondweed at a time when it is actively growing and when many native species remain dormant (Netherland et al. 2000). Moreover, curlyleaf pondweed, like some other invasive plants, has low carbohydrate reserves in early spring (Madsen 1997b, Woolf and Madsen 2003) and may be more sensitive to lower doses of herbicides at this time. In small-scale studies, endothall has been shown to effectively control curlyleaf pondweed and reduce turion formation at water temperatures of 16 ^{o}C, when exposure times of 24 to 72 hr were maintained (Poovey et al. 2002). Based on the results of small-scale herbicide evaluations, a multi-year field study was initiated to demonstrate the use of early spring applications of endothall for selective control of curlyleaf pondweed.

MATERIALS AND METHODS: In summer 1999, four lakes were selected in cooperation with the Minnesota Department of Natural Resources (MNDNR) for use in this evaluation (Table 1). Selection criteria included: 1) lakes less than 60 ha (125 to 250 acres) in size and 2) lakes with a large percentage of the littoral zones occupied by curlyleaf pondweed. Using these criteria, Cleary Lake and Hurley Lake were untreated reference lakes, and Blackhawk and Schwanz were designated as herbicide-treated lakes. All of these lakes are within the Minneapolis/St. Paul, MN, metropolitan area and serve as recreational resources for local residents – with the exception of Hurley Lake, which is utilized for storm water retention and closed for public use.

Table 1
Summary of pretreatment vegetation coverage, transects and sampling points in Cleary, Hurley, Blackhawk, and Schwanz Lakes, Minnesota[1]

Lake	Lake Area, ha	Mean Depth, m	Native Plant Coverage, %	Curlyleaf Pondweed Coverage, %
Cleary (reference)	49	1.5	74	74
Hurley (reference)	2	0.9	100	100
Blackhawk (treated)	14	1.5	98	73
Schwanz (treated)	5	1.8	31	39

[1] Transects/Occurrence Sampling Points/Biomass Sampling Points: Cleary 10/54/18; Hurley 3/9/9; Blackhawk 11/41/41; Schwanz 7/27/10.

Herbicide Applications: Lakes were treated with a liquid formulation of the dipotassium salt of endothall (Aquathol® K, Cerexagri, King of Prussia, PA) using a tank injection system with 3-m drop hoses mounted on the stern of a boat. Herbicide was applied as whole lake treatments where the entire lake volume was treated to provide an aqueous concentration of 1.5 mg active ingredient (ai)/L in 2000 and 1.0 mg ai/L in 2001-2003. Endothall was applied in mid April to early May (2000-2003) when water temperatures reached 12 to 15 ^{o}C.

Assessment of Plant Communities: Pretreatment plant evaluations (species diversity as percent occurrence, and plant abundance as biomass) were conducted from 15 to 20 August 1999 and in mid-April 2000. Post-treatment plant evaluations were conducted in mid-June and mid-August 2000 to 2003, and in mid-April 2001 to 2004. Sampling times were chosen based on life cycle events of curlyleaf pondweed and the native plant communities. April samples assessed early spring growth of curlyleaf pondweed, before native plants had sprouted/germinated, and were used

to determine if further herbicide applications were warranted. June samples assessed peak growth of curlyleaf pondweed (which declines dramatically by early July), and peak growth of early-growing native plants, such as pondweeds. August samples assessed peak growth of later-growing native plants, such as coontail.

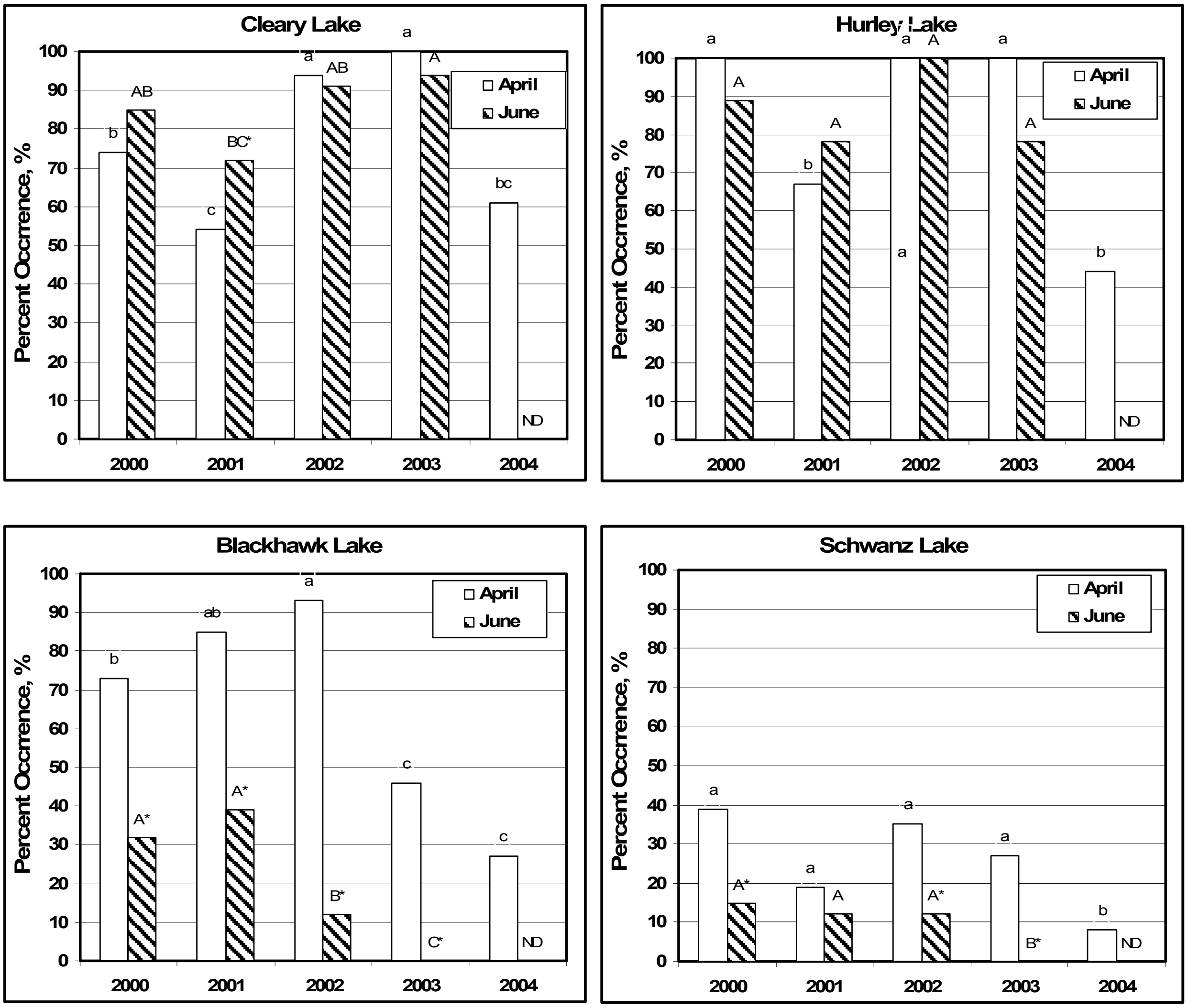
Plant species diversity was measured by quantifying the percent occurrence of each plant species using a method developed by Madsen (1999). In August 1999, transects with sample points separated by 25 m were established in the littoral zone (defined as a depth $\leq$ 4.5 m by the MNDNR for operational plant control) for each lake (Table 1) and recorded using a Garmin GPS III Plus unit. At each sample point, a double rake head (36 cm in length) attached to a rope was thrown twice, approximately 3 m distance away from the sampling boat, and dragged along the bottom back to the boat. Plants contained on the rake head from each throw, and plants that could be clearly seen below the water from the boat, were identified to species. Species diversity (percent occurrence of plant species) was calculated by dividing the number of points where a particular species was present by the total number of sample points in the littoral zone. Post-treatment data were compared to pretreatment data using Chi Square ($p \leq 0.05$; after Madsen (1999)).

Plant abundance (biomass) was evaluated by randomly selecting one third of the sample points from species diversity evaluations and harvesting plants at each point. Biomass samples were collected using a 36-cm rake head attached to a 3-m pole. At each sample point, the rake was lowered from the boat perpendicular to the bottom and then raised up to the water surface while slowly being twisted in a clockwise direction. Plants from each sample toss were removed from the rake head, separated by species, and oven dried at 65^{o} C to a constant weight. Biomass data were log transformed to preserve the assumptions of normality and equal variance, and post-treatment data were compared to pretreatment data using analysis of variance (ANOVA).

RESULTS: An overview of the size and plant community for the four study lakes is shown in Table 1. Lakes ranged in size from 2 to 50 ha, and littoral zones (by MNDNR definition) comprised 100 percent of the respective lake areas. Curlyleaf pondweed had formed nuisance-level surface canopies over large areas in all lakes, with portions of the littoral zones infested with that plant ranging from 39 to 100 percent. Coontail was the dominant native plant species in all lakes when the study was initiated.

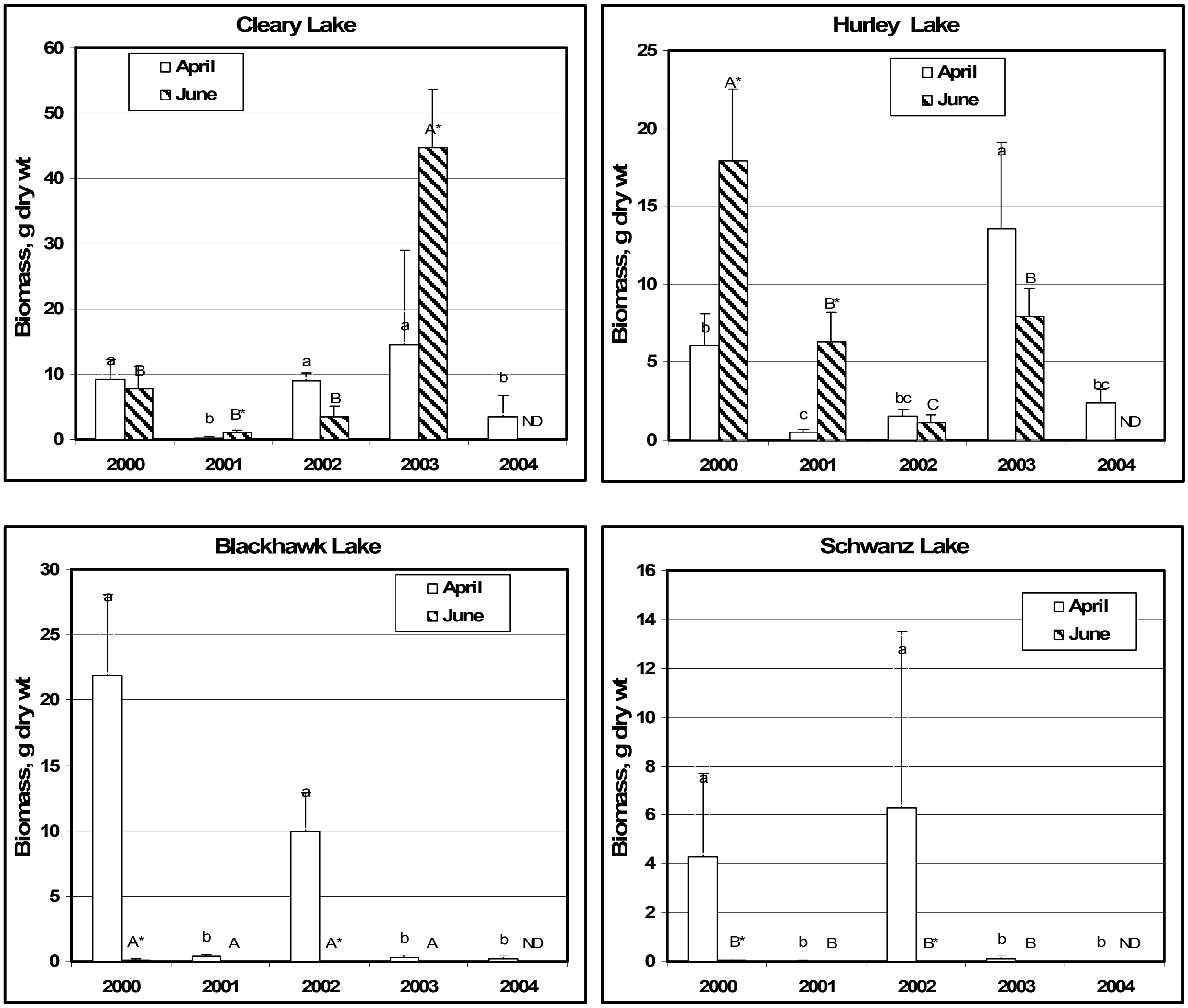
Since April and June were the most critical sampling times for curlyleaf pondweed growth, data for that species are summarized for those months only. In August, curlyleaf pondweed was extremely scarce or non-existent in all lakes – reference and treated (data not shown), due to its life cycle characteristics.

Assessments of occurrence and abundance for curlyleaf pondweed (Figures 1 and 2) showed very different trends between reference lakes and endothall-treated lakes over the study period. In the reference lakes, occurrence of curlyleaf pondweed averaged 80 percent in April, and 86 percent in June (Figure 1). However, occurrence of that plant in the endothall-treated lakes averaged 45 percent in April and only 14 percent in June, with none being found in the last year of the study. Trends in abundance were similar, with biomass for June (the peak month for curlyleaf pondweed growth) averaging 8.3 g dry weight in the reference lakes to essentially no biomass in the endothall-treated lakes (Figure 2).



1. Upper case letters indicate a significant difference between years for August plant evaluations.
2. Lower case letters indicate a significant difference between years for June plant evaluations.
3. * Indicates significant difference between June and August plant evaluations for each year.
4. Cleary Lake, n = 54; Hurley Lake, n = 9; Blackhawk Lake, n = 41; Schwanz Lake, n = 27.

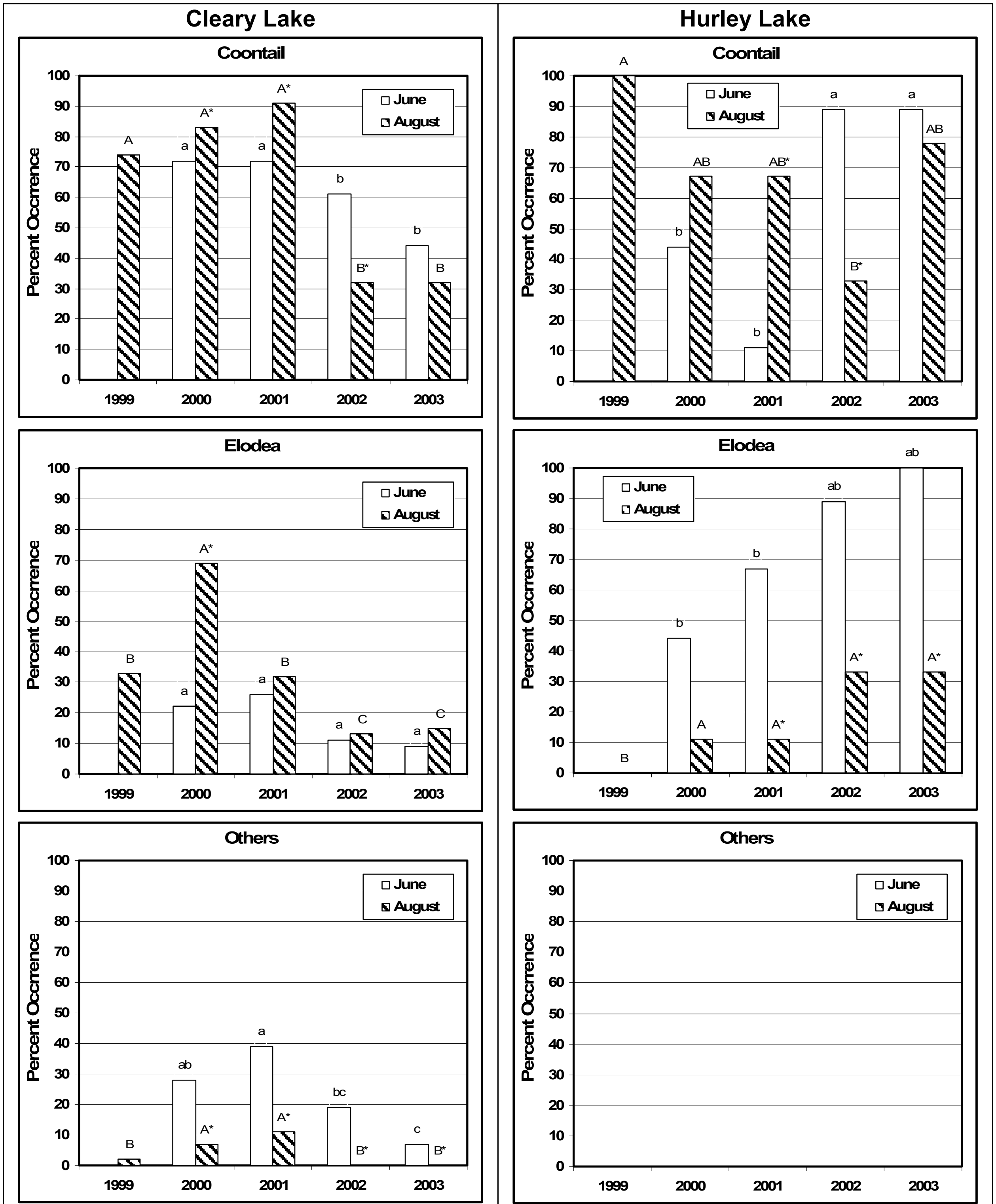
Figure 1. Curlyleaf pondweed percent occurrence in Cleary and Hurley (reference) and Blackhawk and Schwanz (treated) Lakes, MN, April and June 2000-2004.



1. Upper case letters indicate a significant difference between years for August plant evaluations.
2. Lower case letters indicate a significant difference between years for June plant evaluations.
3. * Indicates significant difference between June and August plant evaluations for each year.
4. Cleary Lake, n = 18; Hurley Lake, n = 9; Blackhawk Lake, n = 14; Schwanz Lake, n = 10.

Figure 2. Curlyleaf pondweed abundance (mean biomass ±1 SE, g dry weight) in Cleary and Hurley (reference) and Blackhawk and Schwanz (treated) Lakes, MN, April and June 2000-2004.

Assessments of occurrence (Figures 3 and 4) and abundance (Figures 5 and 6) for native plants showed somewhat similar trends between reference and endothall-treated lakes over the study period. In reference lakes, percent occurrence averaged 65 percent for coontail, 24 percent for elodea, and 2 percent for other species in August. In the endothall-treated lakes, percent occurrence averaged 50 percent for coontail, 22 percent for elodea, and 15 percent for other species.



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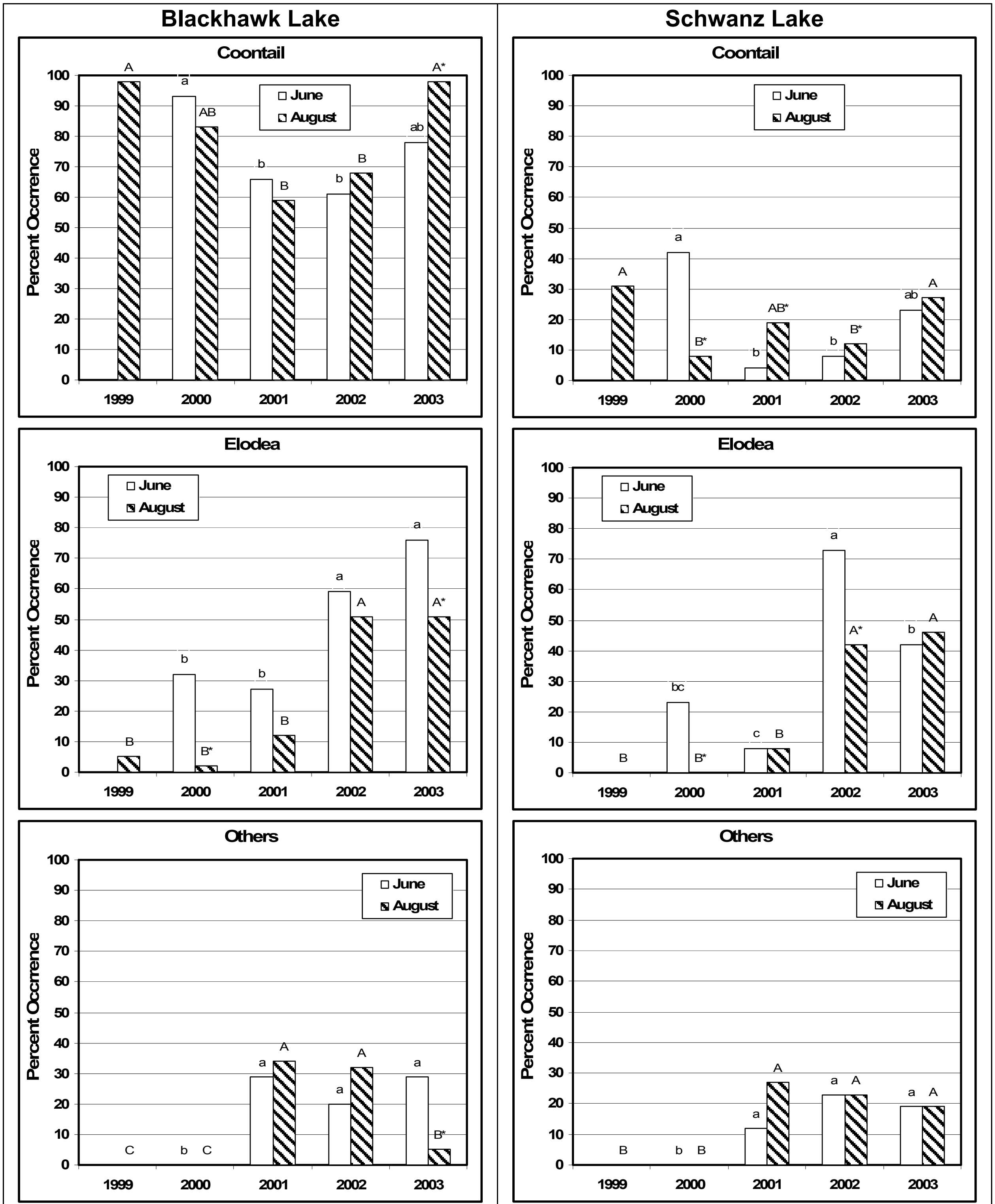
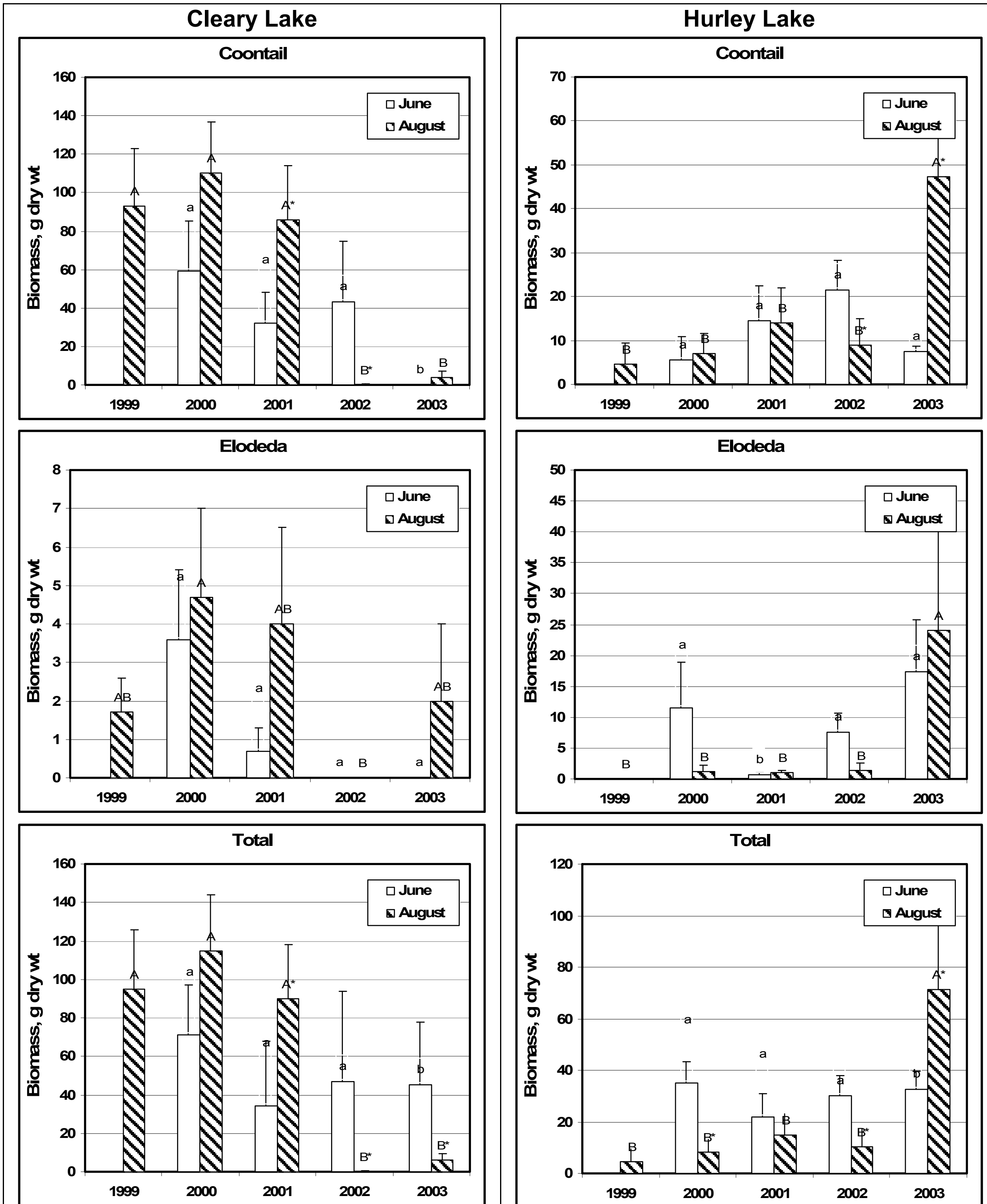
2. Lower case letters indicate a significant difference between years for June plant evaluations.
3. * Indicates significant difference between June and August plant evaluations for each year.
4. Cleary Lake, n = 54; Hurley Lake, n = 9.

Figure 3. Percent occurrence of native plants in untreated reference lakes, Cleary and Hurley, MN, 1999-2003.



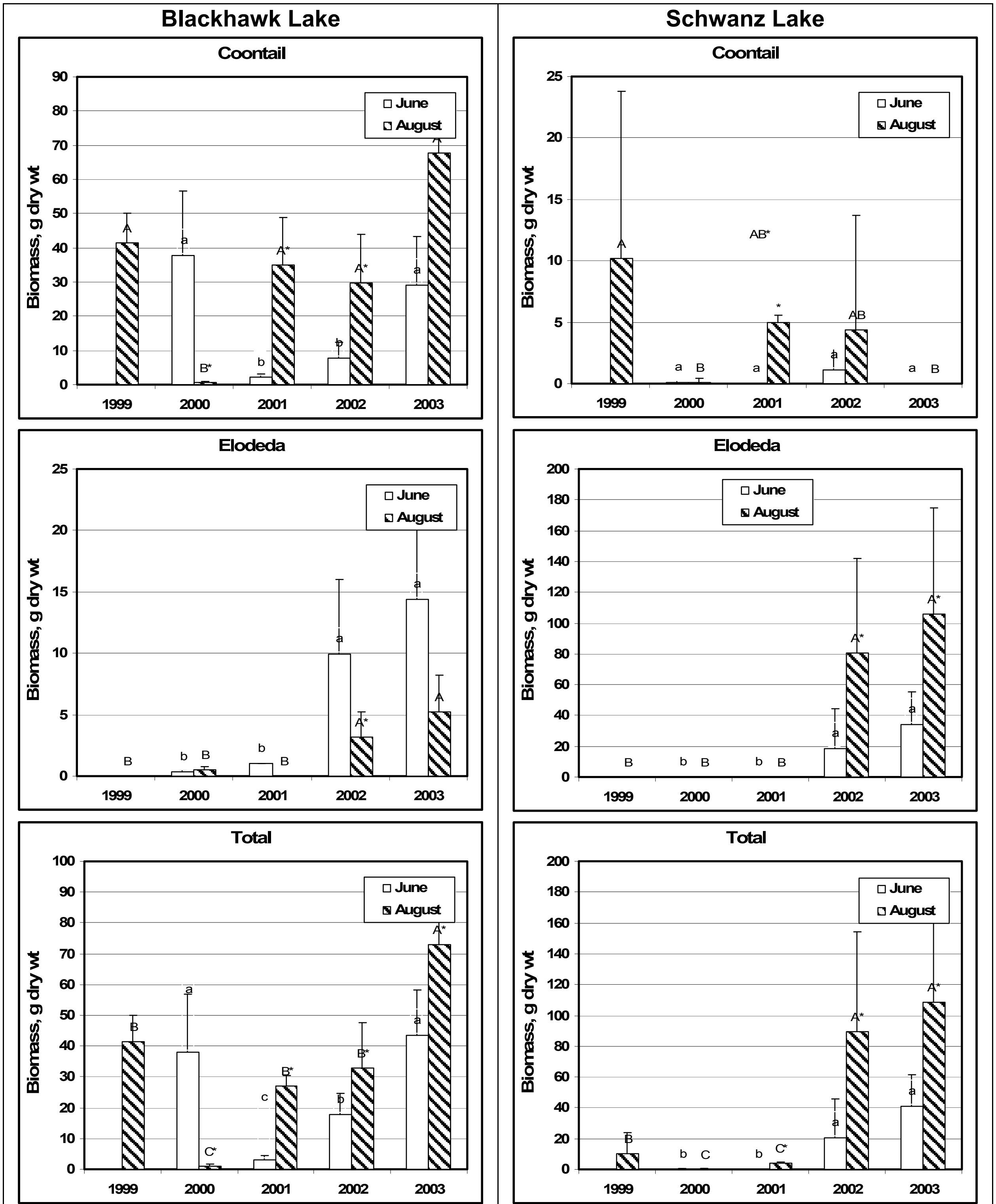
1. Upper case letters indicate a significant difference between years for August plant evaluations.
2. Lower case letters indicate a significant difference between years for June plant evaluations.
3. * Indicates significant difference between June and August plant evaluations for each year.
4. Blackhawk Lake, n = 41; Schwanz Lake, n = 27.

Figure 4. Percent occurrence of native plants in herbicide treated lakes, Blackhawk and Schwanz, MN, 1999-2003.



1. Upper case letters indicate a significant difference between years for August plant evaluations.
2. Lower case letters indicate a significant difference between years for June plant evaluations.
3. * Indicates significant difference between June and August plant evaluations for each year.
4. Cleary Lake, n = 18; Hurley Lake, n = 9.

Figure 5. Plant abundance (mean biomass ±1 SE, g dry weight) of native plants in untreated reference lakes, Cleary and Hurley, MN, 1999-2003.



1. Upper case letters indicate a significant difference between years for August plant evaluations.
2. Lower case letters indicate a significant difference between years for June plant evaluations.
3. * Indicates significant difference between June and August plant evaluations for each year.
4. Blackhawk Lake, n = 14; Schwanz Lake, n = 10.

Figure 6. Plant abundance (mean biomass ±1 SE, g dry weight) of native plants in herbicide treated lakes, Blackhawk and Schwanz, MN, 1999-2003.

Key plant community changes measured in each lake summarized below:

Cleary Lake – untreated reference: Curlyleaf pondweed occurrence and abundance data for Cleary Lake are presented in Figures 1 and 2, and these parameters varied significantly on an annual basis. The lowest spring (April and June) values of occurrence (54 percent) and abundance (0.2 g) were measured in 2001. This followed an early and prolonged period of snow and ice cover (mid-November 2000 through early April 2001), which also resulted in a winter fish kill in February 2001. Occurrence and abundance levels had recovered in 2002, with peak occurrence (100 percent) and abundance (44.6 g) of curlyleaf pondweed being measured in 2003. Overall, maximum levels of curlyleaf pondweed occurred between April and June, and the plants were mostly gone by August (data not reported), which followed normal senescence in late spring or early summer.

Occurrence and abundance data for native plants for Cleary Lake are presented in Figures 3 and 5. Initially, coontail was the dominant species with respect to plant abundance and accounted for 95 to 98 percent of the biomass (1999 through 2001). Elodea was the next most common plant and comprised most of the remaining biomass. Other species were comprised primarily of leafy pondweed (*Potamogeton foliosus* Raf.) and sago pondweed. Following the June 2002 plant evaluations, the native plant population declined significantly. Coontail biomass in August 2002 was only 4.1 g compared to a peak of 110 g in August of 2000. Occurrence of coontail also declined from a peak of 91 percent in August 2001 to only 32 percent in August 2002. The decline in coontail and elodea continued into the summer of 2003. A severe blue green algae bloom was observed in August 2002, which may have contributed to this decline. Blue green algae, particularly those that produce toxins, have been reported to limit growth of aquatic macrophytes (Casanova et al. 1999, LeBlanc et al. 2005). No major recovery of native plants occurred during the study, however curlyleaf pondweed expanded in Cleary Lake in 2003 with peak levels of occurrence and abundance recorded in June 2003.

Hurley Lake – untreated reference: Curlyleaf pondweed occurrence and abundance data for Hurley Lake are presented in Figures 1 and 2. These parameters varied significantly on an annual basis. The lowest spring (April and June) values of occurrence (44 percent) and abundance (0.5 g) were measured in 2001 and 2004. In 2001, similar biomass levels were measured in Cleary Lake, and were probably the result of a severe winter. Peak occurrence (100 percent) and abundance (17.9 g) were measured in 2000. Similar to Cleary Lake, maximum levels of curlyleaf pondweed occurred between April and June, and the plants were mostly gone by August (data not reported), which followed normal senescence in late spring or early summer.

Occurrence and abundance data for native plants are presented in Figures 3 and 5. Coontail and elodea were the only two native species found in Hurley Lake and accounted for all of the biomass, which was similar between 1999 and 2002 with no significant changes in total biomass. Biomass peaked in August of 2003 at 72.9 g, which was a twofold increase in biomass compared to previous years.

Blackhawk Lake - herbicide treated: Curlyleaf pondweed occurrence and abundance data for Blackhawk Lake are presented in Figures 1 and 2. Every year, curlyleaf pondweed biomass in June was equal to or near zero following endothall treatments, indicating the treatment was effective at providing excellent seasonal control. Percent occurrence of curlyleaf pondweed was significantly

reduced in June compared to April; however, plants were present in 12 to 39 percent of the sample sites. Based on visual observations, these were very small plants attached to turions and may have sprouted in spring after the herbicide applications. Initial biomass in April varied significantly between years. Biomass at the time of treatment in April 2001 was low (0.5 g), probably the result of a severe winter, as similar biomass levels were measured in the untreated reference lakes, Cleary and Hurley. Biomass significantly increased in 2002 indicating that turions in the sediment were still viable. Biomass in 2003 and 2004 was significantly lower than in 2000 and 2002, which was contrary to results seen in the reference lakes (Cleary and Hurley), indicating that repeated endothall treatments may have impacted the sediment turion bank as nuisance levels of the plant were decreasing. In June 2003 following the fourth year of treatment, no curlyleaf pondweed was observed. In April 2004, some curlyleaf pondweed returned, but was less than 30 percent occurrence and below nuisance levels; therefore, additional endothall treatments were not required.

Percent occurrence and abundance data for native plants are presented in Figures 4 and 6. Initially, coontail was the dominant species and accounted for more than 95 percent of the biomass. Elodea was the next most common plant and comprised most of the remaining biomass. No other native plant species were found in 1999 and 2000. Coontail biomass in August 2000 was only 0.5 g compared to a 41 g in August 1999 and 38 g in June 2000. The decline probably resulted from a severe storm in July 2000. Water levels rose 3 m above normal, causing much of the coontail to wash away. High water levels continued for more than a month. By August 2001, coontail biomass had recovered.

By 2001, other native plant species were found in 29 to 34 percent of the sample sites, including leafy pondweed, flat stem pondweed, sago pondweed, najas, horned pondweed, and chara. In 2002 and 2003 elodea biomass increased significantly compared to previous years.

Schwanz Lake - herbicide treated: Curlyleaf pondweed percent occurrence and abundance data are presented in Figures 1 and 2, and were similar to results seen in Blackhawk Lake. Curlyleaf pondweed biomass in June was equal to or near zero following herbicide treatments, indicating that endothall was effective at providing excellent seasonal control. Although April pretreatment evaluations showed that percent occurrence of curlyleaf pondweed did not vary between years, there were significant differences in biomass. Like Blackhawk, the biomass in untreated reference lakes, Cleary and Hurley, at the time of treatment in April 2001 was low (0.02 g), probably the result of a severe winter. A fish kill occurred in Schwanz Lake, as in the reference Hurley Lake, during the winter of 2000/2001.

Curlyleaf pondweed biomass increased significantly in 2002 indicating that the sediment still contained viable turions. However, biomass in 2003 and 2004 was very low, and was contrary to results seen in the reference lakes (Cleary and Hurley), indicating that repeated endothall treatments were beginning to provide long-term control. Percent occurrence of curlyleaf pondweed was significantly reduced in June compared to April, but plants were still present in 12 to 15 percent of the sample sites. Based on visual observations, these were very small plants attached to turions, indicating they may have sprouted in spring after the herbicide applications. In June 2003 following the fourth treatment, no curlyleaf pondweed was observed. In April 2004, some curlyleaf pondweed returned, but occurred in less than 10 percent of the sample sites and was well below nuisance levels; therefore, additional endothall treatments were not required.

Percent occurrence and abundance data for native plants are presented in Figures 4 and 6. Initially, coontail was the dominant species and accounted for more than 95 percent of total plant biomass. Elodea was the only other native plant and composed most of the remaining biomass in 1999 and 2000. Coontail biomass in August 2000 was only 0.1 g compared to a 10 g in August 1999. The decline probably resulted from a severe storm that caused water levels to rise to 3 m above normal and remain high for 1.5 months, causing much of the coontail to wash away. By August 2001, coontail biomass had recovered. In addition, other native plant species were found in 12 to 27 percent of the sample sites, and included leafy pondweed, sago pondweed, najas, horned pondweed (*Zannichellia palustris* L.), and muskgrass (*Chara spp*.). In 2002 and 2003 elodea biomass and percent occurrence increased significantly compared to previous years, and became the dominant native plant species.

SUMMARY: A series of early spring (mid-April to early May), low-dose applications (1 to 1.5 mg ai/L) of endothall (as Aquathol® K) effectively controlled curlyleaf pondweed in Blackhawk and Schwanz Lakes, MN. Control was nearly 100 percent with respect to plant abundance and approximately 85 percent with respect to percent occurrence of curlyleaf pondweed plants. These remaining plants represented occasional young individuals that sprouted from turions after each herbicide application and were well below nuisance levels of occurrence and abundance. Limited populations of curlyleaf pondweed continued to recur each year from the turion bank in the sediment. However, that recurrence declined in 2003, following the third endothall treatment in 2002, and continued to decline until additional treatments were not required in 2004 to maintain curlyleaf pondweed control. In contrast, the untreated reference lakes, Cleary and Hurley, continued to be dominated by nuisance levels of curlyleaf pondweed.

Native plant communities were not adversely affected by repeated whole lake endothall treatments, as these populations increased in abundance and percent occurrence during this study. Previously undetected pondweed species were found in 2001 through 2003. During the same period, native plant communities in Cleary Lake (an untreated reference) significantly declined, while growth of curlyleaf pondweed increased. Results from this multi-year study suggest that selectively removing curlyleaf pondweed early in the growing season can enhance growth of some native plants. Also, the early removal of curlyleaf pondweed prevents the formation of new reproductive turions, which are the source of its annual reinfestation. Curlyleaf pondweed was significantly reduced following 4 years of whole lake endothall treatments, but not eliminated. The prescriptive and selective use of herbicides (e.g. as early season, low-dose applications of endothall) as a maintenance tool can prevent exotics from reaching nuisance levels and protect important native plant communities.

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